

Mitosis, Meiosis and Fertilization

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When you fall and scrape the skin off your hands or knees, how does your body make new skin cells to replace the skin cells that were scraped off? How does your body make sure each new cell has all the chromosomes it needs to have? How does a baby get his or her genes?

In this activity you will learn some of the answers to these questions. We will begin by reviewing what chromosomes and genes are.

Chromosomes and Genes

Each **chromosome** contains one long molecule of DNA. This molecule of DNA contains many genes. Each **gene** is a segment of the DNA molecule that gives the instructions for making a protein. For example:

- One gene gives the instructions for making **hemoglobin**, a protein that carries oxygen in red blood cells.
- Another gene gives the instructions for making a protein enzyme which helps to make the pigment **melanin** (a molecule that contributes to our skin and hair color).
- Other genes give the instructions for making the proteins in our noses that respond to different types of smells.

These genes are all contained in the long DNA molecule in one chromosome. Each cell in your body has two copies of this chromosome. These two chromosomes are called a pair of **homologous chromosomes**. The DNA in both homologous chromosomes contains the same genes at the same locations in the chromosome. However, the two homologous chromosomes may have different versions of a gene. The two different versions of the same gene are called **alleles**. Different alleles result in different versions of the protein, and different versions of the protein can result in different characteristics. The table gives some examples.

Allele		Protein		If both homologous chromosomes have this allele, the person has:
S	→	normal hemoglobin	→	normal blood
s	→	sickle cell hemoglobin	→	sickle cell anemia (sickle shaped red blood cells that can block blood flow → pain, etc.)
A	→	normal enzyme for melanin production	→	normal skin and hair color
a	→	defective enzyme for melanin production	→	very pale skin and hair color (albino)
R	→	normal protein that responds to an odor	→	can smell that odor
r	→	protein that does not respond to the odor	→	can not smell that odor

¹ Teachers are encouraged to copy this student handout for classroom use. A Word file (which can be used to prepare a modified version if desired), Teacher Preparation Notes, comments, and the complete list of our hands-on activities are available at http://serendip.brynmawr.edu/sci_edu/waldron/.

We appreciate the help of Philadelphia high school teachers who contributed valuable suggestions for revision of this activity.

Each human cell has 23 different pairs of homologous chromosomes. Each of these pairs of homologous chromosomes has different genes that give the instructions for making different kinds of proteins. The following diagram shows a few of the genes in the two copies of chromosomes 11 and chromosome 4 in a girl named Tania.

Chromosome 11 |S allele| |r allele| |a allele|

Chromosome 11 |S allele| |r allele| |a allele|

Chromosome 4 |D allele|

Chromosome 4 |d allele|

Chromosome 4 has a gene that gives the instructions to make a protein that helps to regulate bone growth. The **D** allele of this gene results in dwarfism; a person who has two copies of the **d** allele has normal height.

Diagrams like this are very oversimplified. For example, each of these chromosomes also has hundreds of additional genes.

Questions

1. Fill in the blanks of the following sentences.

A chromosome contains one long _____ molecule. Each gene in this molecule gives the instructions for making _____.

Both chromosomes in a pair of _____ chromosomes have the same _____, but the two chromosomes may have different _____.

Chromosomes that are not homologous have different _____ which give the instructions for making different kinds of proteins.

2. Use the diagram above and the table on page 1 to answer the following questions.
What type of hemoglobin does Tania have in her red blood cells?

What color skin and hair does she have?

3. For your body to be healthy, each cell needs to have a complete set of chromosomes. Explain why your body would not be healthy if each of your cells did not have a complete set of chromosomes.

Mitosis -- How Your Body Makes New Cells

How many cells do you think your body has?

Why does your body need to have lots of cells?

Each of us began as a single cell, so one important question is:

How did that single cell develop into a body with more than a trillion cells?

The production of such a large number of body cells is accomplished by many, many repeats of a cycle of **cell division** in which one cell gives rise to two cells, each of which in turn gives rise to two cells, etc. Thus, cell division is needed for growth.

Even in a fully grown adult, cells still undergo cell division. Why is this useful? Think about your skin, for example.

On average, each red blood cell in your body dies after approximately 4 months. Thus, all the red blood cells that were in your body a year ago have died and been disposed of many months ago. Could you live with no red blood cells in your blood?

How are new red blood cells produced?

The two cells that come from the division of one cell are called **daughter cells**. (It may seem odd, but the cells produced by cell division are called daughter cells, even in boys and men.) Each of the daughter cells needs to have a complete set of chromosomes.

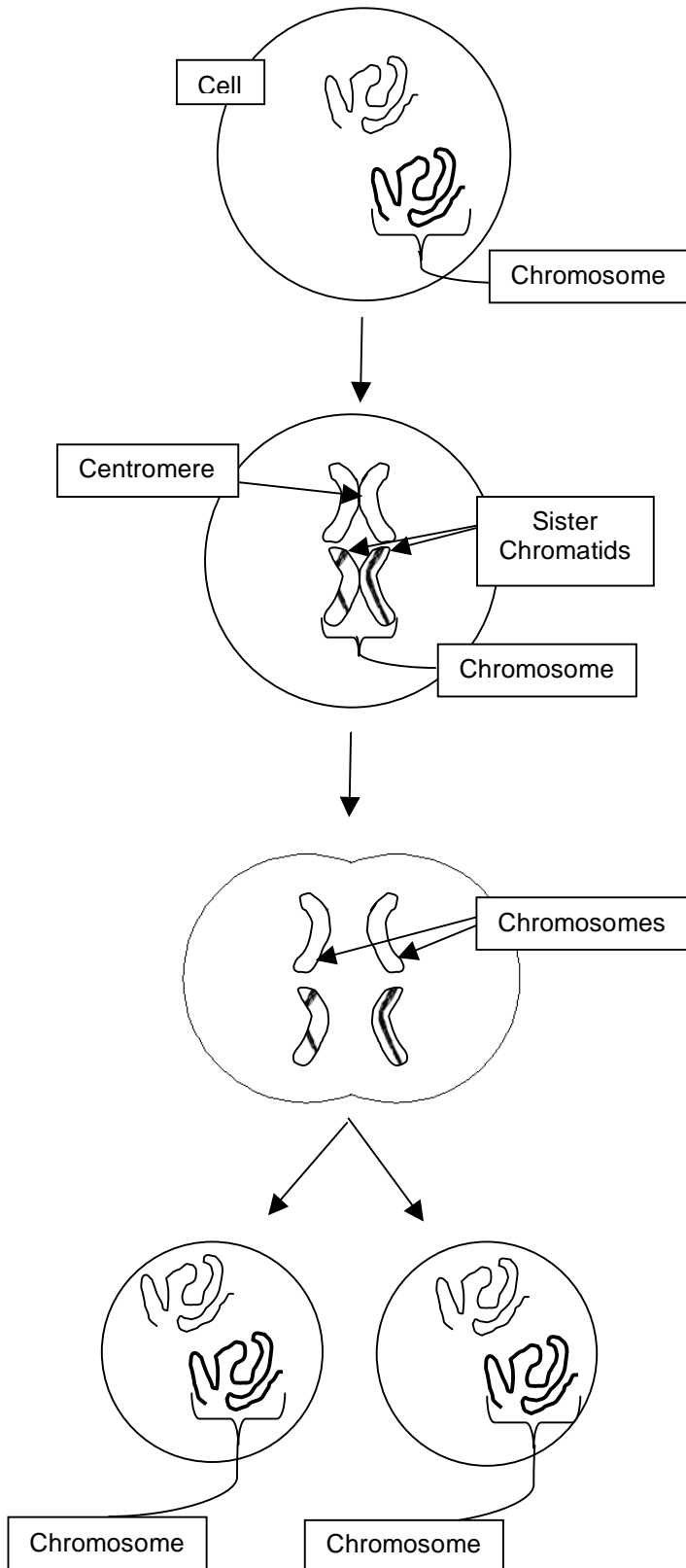
How each daughter cell gets a complete set of chromosomes

In each cycle of cell division, the cell first makes a copy of the long strand of DNA in each of the chromosomes. This is called **DNA replication**.

After the DNA strand in each chromosome has been copied, the cell undergoes a type of cell division called **mitosis**. Mitosis carefully separates the two copies of each chromosome to opposite ends of the dividing cell, so each daughter cell ends up with a complete set of chromosomes.

At the very beginning of mitosis each of the chromosomes changes shape. While the cell is carrying out its normal activities, the DNA molecule of each chromosome is a long thin thread with the DNA spread out so the genes can be active and give the instructions for making proteins. In a human cell that is ready to begin mitosis, the DNA has replicated so there is a double copy of each of the 46 chromosomes (23 pairs of homologous chromosomes). You can imagine that it would be difficult to reliably separate the two copies of each of the 46 long thin chromosomes. Therefore, in preparation for mitosis, the DNA is **condensed** into compact chromosomes, like those shown in the second diagram on the next page.

Mitosis -- The Basics



Cell with Two Chromosomes

To get ready for mitosis, the cell makes a copy of the long strand of DNA in each chromosome. The two copies of each DNA molecule are attached to each other. (You can't see the two copies until the beginning of mitosis which is shown in the next diagram.)

Beginning of Mitosis

Once the DNA strand in a chromosome has been copied, the two copies of the DNA are condensed into two **chromatids** which are attached to each other at a **centromere**. The two chromatids are often called **sister chromatids** because they are identical.²

At the beginning of mitosis, each chromosome consists of a pair of sister chromatids, and the chromosomes are lined up in the center of the cell.

Mitosis

During mitosis the two sister chromatids of each chromosome separate and become independent chromosomes.

Mitosis Completed

Mitosis has produced two new daughter cells. Each daughter cell has received one copy of each chromosome, so each daughter cell has a complete copy of all the DNA in the original cell.

² The two attached chromatids are called sister chromatids, even in the cells of boys and men.

The drawings on page 4 show the basic process of mitosis in a cell which has only two chromosomes. These two chromosomes are a pair of homologous chromosomes. As you know, the two different homologous chromosomes may have different alleles for each gene. In contrast, the two sister chromatids of a chromosome have identical alleles for each gene, because the process of copying DNA results in exact copies of the original alleles.

Questions

For the diagram on page 4, assume that the two homologous chromosomes have different alleles for the gene for hemoglobin.

How many copies of each allele for hemoglobin are there in the cell in the second drawing?

How many copies of the gene for hemoglobin are there in this cell?

How many copies of each allele for hemoglobin are there in each cell in the bottom drawing?

How many copies of the gene for hemoglobin are there in each of these cells?

Modeling Mitosis

To model mitosis you will use a pair of sockosomes to represent the pair of homologous chromosomes. You will begin with sockosomes which have two socks joined at the heel to represent the sister chromatids joined together, similar to the chromosomes in the second drawing on page 4. Thus, you will model mitosis, beginning after the DNA has been replicated and condensed.

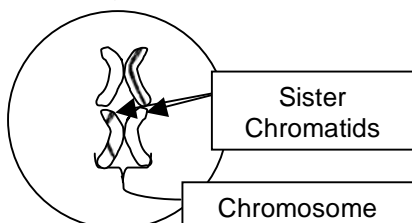
Both sockosomes are the same color, to indicate that you have a pair of homologous chromosomes which both have the same genes. As shown in the figure on page 4, one of your model chromosomes has a stripe on both chromatids and the other sockosome has no stripes; this indicates that the two homologous chromosomes have different alleles for many of the genes, even though they have the same genes. The letters on the pieces of tape on these sockosomes represent one or more of the alleles on each chromosome.

Together with your partner, use your sockosomes to demonstrate how the two chromosomes line up at the beginning of mitosis. Then demonstrate how the sister chromatids of each chromosome separate during mitosis and become separate chromosomes, one of which goes to each daughter cell.

Questions

1. Once a new daughter cell has been formed, each chromosome unwinds into a long thin thread so the genes can become active and give the instructions for making proteins. Suppose the daughter cell needs to divide again in order to produce more cells (for example, in a growing child). Before the daughter cell can divide again, what has to happen to the chromosomes?

2. Your partner prepares the sockosomes so you can demonstrate how mitosis takes place in one of the daughter cells. When you see what your partner has done (shown in the diagram below), you realize that this arrangement of the sockosomes could never occur in a real cell. What is wrong? Explain why sister chromatids could not have different alleles.



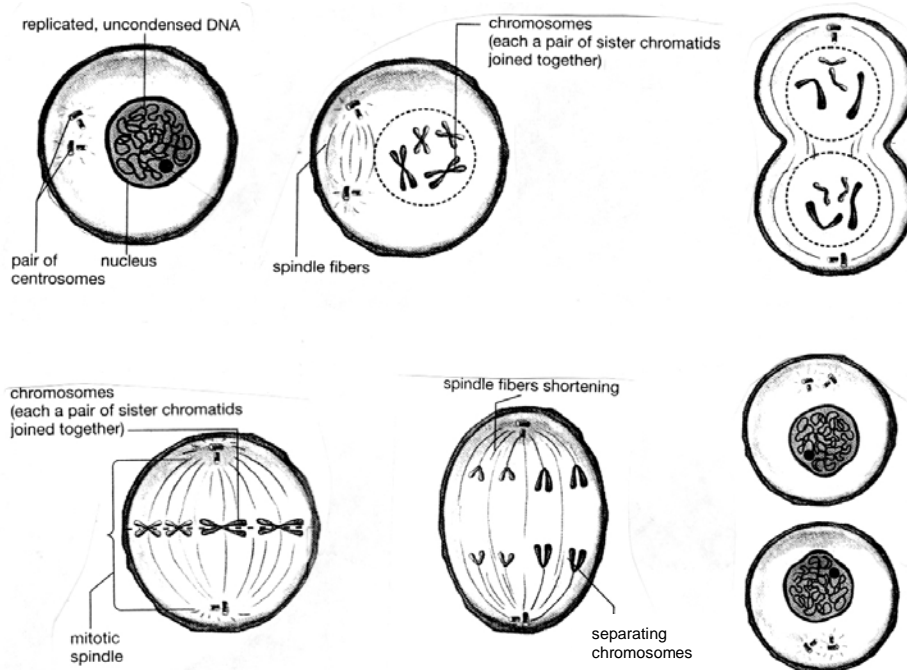
More about how mitosis occurs in real cells

The following steps ensure that each daughter cell receives a complete set of chromosomes.

1. DNA is copied (called replication).
2. DNA is condensed into compact chromosomes (each with two sister chromatids). These are easier to move than the long thin chromosomes observed in a cell which is not undergoing cell division. **Spindle fibers** which will move the chromosomes begin to form.
3. Spindle fibers line the chromosomes up in the middle of the cell.
4. Spindle fibers pull the sister chromatids apart toward opposite ends of the cell.
5. The cell begins to pinch in half, with one set of chromosomes in each half.
6. Two daughter cells are formed.

Questions

1. For each of the figures below, give the number of the corresponding step described above. Draw arrows to indicate the sequence of events during mitosis. (For simplicity, the figures show cells that have only 4 chromosomes (2 pairs of homologous chromosomes), but the basic process is the same as in human cells which have 46 chromosomes.)



2. Pairs of homologous chromosomes are shown in four of these drawings; circle and label each pair of homologous chromosomes (HC).
3. Use an * to mark the arrow you drew which shows when sister chromatids separate to become individual chromosomes.

Modeling mitosis with two pairs of a homologous chromosomes

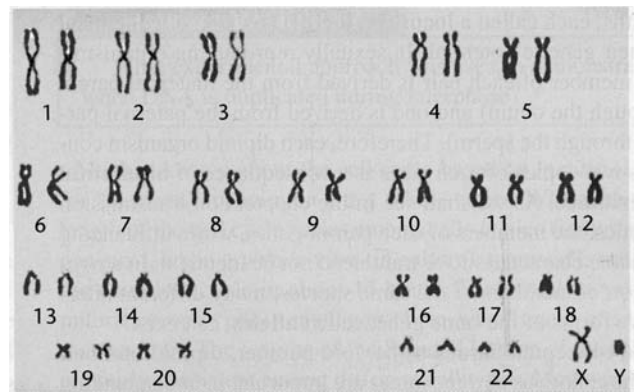
Find two sockosomes in your group that have the two different alleles for the gene that can result in albinism (**A** for normal melanin production and normal skin and hair color and **a** for albinism). Next, find two sockosomes in your group that have the two different alleles for the gene that can result in dwarfism (**D** for dwarfism and **d** for normal height). Put these four sockosomes in a pile which will represent the two pairs of homologous chromosomes, each with the DNA copied and condensed, so the cell is ready to undergo mitosis. Model the steps in mitosis. Begin by arranging the sockosomes in the pattern observed for chromosomes in a real cell at the beginning of mitosis (see diagram on previous page). Use your arms to represent the spindle fibers. Describe your results by completing the following chart.

	AA or Aa or aa?	DD or Dd or dd?
Which alleles were present in the original cell (before DNA replication)?		
Which alleles are present in each daughter cell produced by mitosis?		

Questions

1. Are the genes in the daughter cells produced by mitosis the same as or different from the genes in the original cell? Explain how this happens.
2. What would happen if a cell did not make a copy of the DNA in its chromosomes before it divided?
3. Why is it important for the chromosomes to line up in the middle of the cell during mitosis?

4. The figure on the right shows a **karyotype**, which is a photograph of a magnified view of the chromosomes from a human cell. Each pair of homologous chromosomes is assigned a number. For example, chromosome 11 is the chromosome we have described with the genes for hemoglobin, smell receptors, and the enzyme which helps to make melanin.



Adapted from Concepts of Genetics 8e
by Klug, Cummings, and Spencer

In the figure, each chromosome has double copies of its DNA, contained in a pair of sister chromatids linked by a centromere. Label the sister chromatids and the centromere in chromosome 3 in the karyotype.

Considering the six steps of cell division described on the previous page, which stages of mitosis can provide chromosomes that have the shape of the chromosomes in a karyotype?

Meiosis -- How Your Body Makes Sperm or Eggs

Mitosis gives rise to almost all the cells in the body. A different type of cell division called **meiosis** gives rise to sperm and eggs.

During **fertilization** the sperm and egg unite to form a single cell called the **zygote** which contains chromosomes from both the sperm and egg.

The zygote undergoes mitosis to begin development of the human embryo which eventually becomes a baby.

Why can't your body use mitosis to make sperm or eggs?

Suppose human sperm and eggs were produced by mitosis. How many chromosomes would each sperm or egg have? _____

If a sperm of this type fertilized an egg of this type, and both the sperm and egg contributed all of their chromosomes to a zygote, how many chromosomes would the resulting zygote have?

In humans, how many chromosomes should a zygote have, so the baby's body cells will each have a normal set of chromosomes? _____

Obviously, if the body used mitosis to make sperm and eggs, the resultant zygote would have too many chromosomes to produce a normal baby. To produce a normal zygote, how many chromosomes should each sperm and egg have? _____

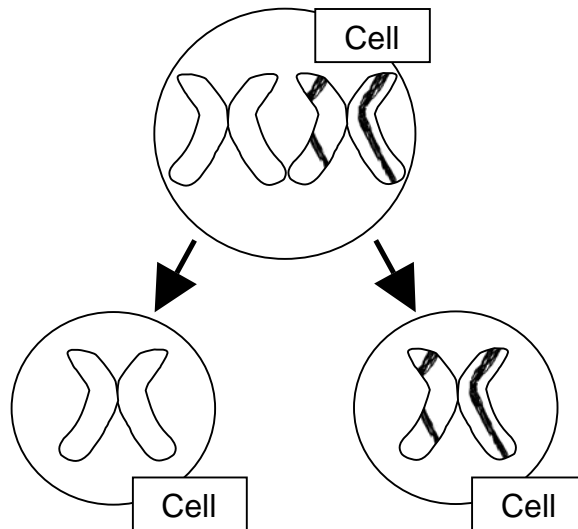
To produce the needed number of chromosomes in sperm and eggs, meiosis reduces the number of chromosomes by half. For example, in humans each sperm and each egg produced by meiosis has only 23 chromosomes, including one chromosome from each pair of homologous chromosomes. Therefore, after an egg and sperm are united during fertilization, the resulting zygote has 23 pairs of homologous chromosomes, one in each pair from the egg and one from the sperm. Thus, the zygote has 46 chromosomes, and when the zygote undergoes mitosis to begin to form an embryo, each cell will have the normal number of 46 chromosomes.

Cells that have two copies of each chromosome (i.e. cells that have pairs of homologous chromosomes) are called **diploid** cells. Most of the cells in our bodies are diploid cells. Cells that only have one copy of every chromosome are called **haploid** cells. Which types of cells in our bodies are haploid?

Before meiosis, the cell makes a copy of the DNA in each chromosome. Then, during meiosis there are two cell divisions, **meiosis I** and **meiosis II**. This reduces the chromosome number by half and produces four haploid daughter cells.

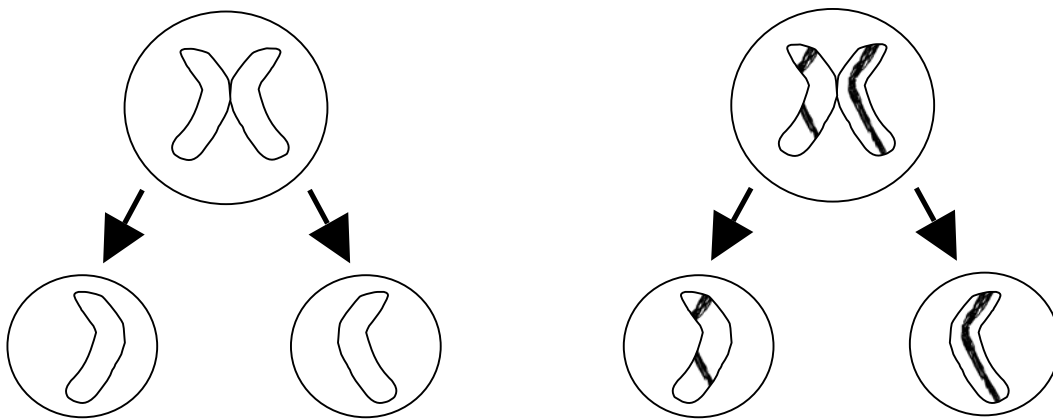
Meiosis I

Meiosis I is different from mitosis because homologous chromosomes line up next to each other and then separate, as shown below. This produces daughter cells with half as many chromosomes as the parent cell, i.e. haploid cells. Notice that each of the daughter cells has a different chromosome from the homologous pair of chromosomes. This means that the alleles in each daughter cell are different.



Meiosis II

Meiosis II is like mitosis. The sister chromatids of each chromosome are separated, so each daughter cell gets one copy of each chromosome in the mother cell.



In the diagram above, label the cells which represent the sperm or eggs produced by meiosis.

Modeling Meiosis

Using one pair of sockosomes, go through each step of meiosis until you are confident that you understand the difference between Meiosis I and Mitosis and the difference between Meiosis I and Meiosis II. For example, what is the difference in the way the pair of homologous chromosomes is lined up in a cell at the beginning of Meiosis I vs. at the beginning of Mitosis?

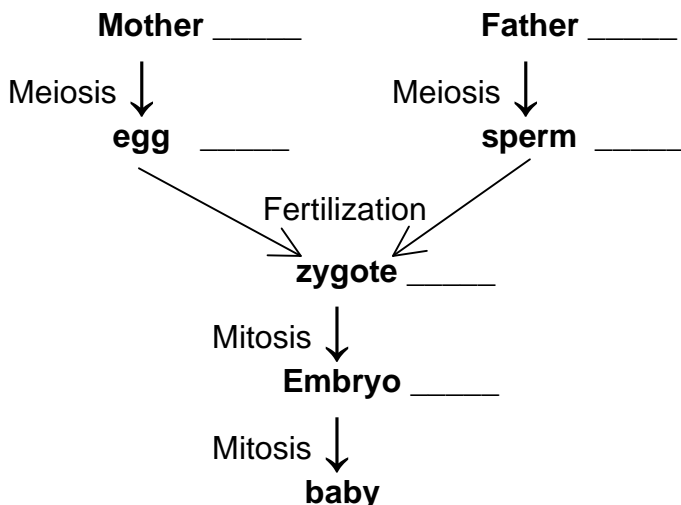
Now, use your group's sockosomes to model meiosis in a cell which has two pairs of homologous chromosomes. Find two sockosomes that have the two different alleles for the gene for albinism (**A** for normal color skin and **a** for albinism). Next, find two sockosomes that have the two different alleles for the gene for dwarfism (**D** for dwarfism and **d** for normal height). Put these four sockosomes in a pile to represent the two pairs of homologous chromosomes, each with the DNA copied so the cell is ready to undergo meiosis. The genetic makeup of this cell is **AaDd**.

Now, use these sockosomes to model the steps in meiosis. Begin by lining up the sockosomes the way real chromosomes line up at the beginning of Meiosis 1. Notice that there is more than one possible way for the sockosomes to line up at the beginning of Meiosis 1. Model meiosis for each way of lining up the sockosomes at the beginning of Meiosis 1.

List all of the different possible combinations of the **A**, **a**, **D** and **d** alleles in the sperm or eggs that can be produced by meiosis.

Questions

1. Describe the differences between the original cell that undergoes meiosis and the daughter cells produced by meiosis.
2. Describe the differences between daughter cells produced by meiosis and daughter cells produced by mitosis.
3. The following diagram provides an overview of the information covered thus far. Review the diagram, and fill in the correct number of chromosomes per human cell in each blank.

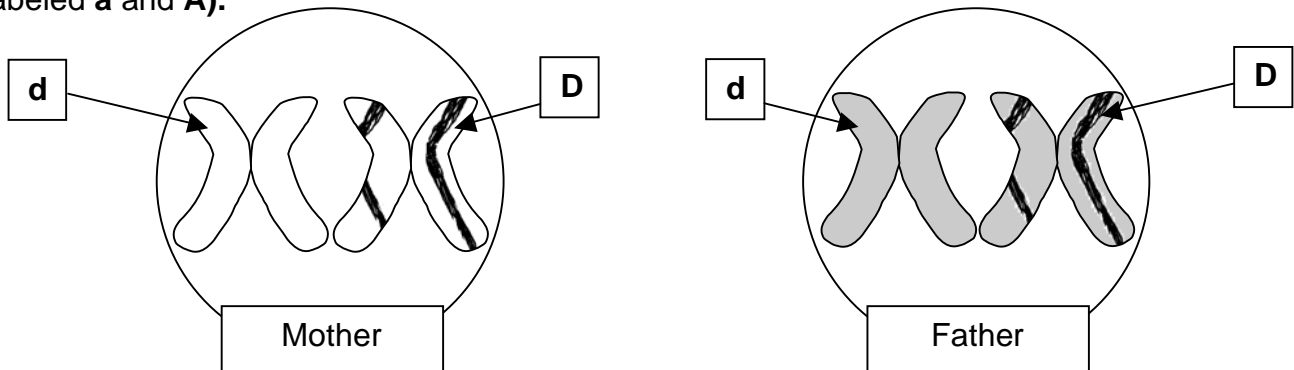


Analyzing Meiosis and Fertilization to Understand Genetics

In this section you will investigate how events during meiosis and fertilization determine the genetic makeup of the zygote, which in turn determines the genetic makeup of the baby that develops from the zygote.

You already know that sisters or brothers can have different characteristics, even though they have the same parents. One major reason for these different characteristics is that the processes of meiosis and fertilization result in a different combination of alleles in each child.

To begin to understand this genetic variability, you will model meiosis and fertilization for a very simplified case where there is only one pair of homologous chromosomes per cell and you will consider just one gene on this chromosome. In both the mother and the father, this gene will have different alleles on the two homologous chromosomes, as shown in the figure below. (Alternatively, you may have four model chromosomes similar to those shown, but labeled **a** and **A**).



Considering just the labeled alleles, how many different types of eggs will be produced by meiosis? _____

List the genetic makeup of the different types of eggs.

Considering just the labeled alleles, how many different types of sperm will be produced by meiosis? _____³

List the genetic makeup of the different types of sperm.

The different types of sperm can fertilize the different types of egg to result in zygotes with different combinations of chromosomes from the mother and the father.

Modeling meiosis and fertilization

One of you should be the father and demonstrate how meiosis produces different types of sperm, and your partner should be the mother and demonstrate how meiosis produces different types of eggs. Next you should use one of the sperm to fertilize one of the eggs to produce a zygote. The resulting zygote will have a pair of homologous chromosomes including one chromosome from the egg and one from the sperm.

³ If you consider all the different genes, there are so many different possible combinations of alleles that each sperm or egg has a unique combination of alleles. Your teacher or textbook can explain how this occurs.

Try to produce as many different types of zygotes as you can by pairing each type of sperm with each type of egg. To do this, it works best to lay the chromosomes out on the table, so you can more easily see the multiple different possible combinations.

List the different combinations of the labeled alleles that can occur in the zygotes produced by fertilization.

Notice that each parent has two different alleles for this gene, but some of the children will have two copies of a single allele (one from their mother and one from their father).

A pair of human parents could produce a great many more different genetic combinations than observed in this simple example. For example, humans have 23 pairs of homologous chromosomes, each with different alleles for multiple genes. As a result of the different ways that the 23 pairs of chromosomes can line up during meiosis 1, many different combinations of chromosomes can be found in the different eggs or sperm produced by one person. If each different type of egg from one mother could be fertilized by each different type of sperm from one father, they could produce zygotes with approximately 70 trillion different combinations of chromosomes! You can see why no two people are genetically alike, except for identical twins who both develop from the same zygote.

Questions

1. How many chromosomes are there in a human skin cell produced by mitosis? _____

How many chromosomes are there in a human sperm cell produced by meiosis? _____

2. Describe the differences between mitosis and meiosis.

3. What are the similarities between mitosis and meiosis?

Down Syndrome

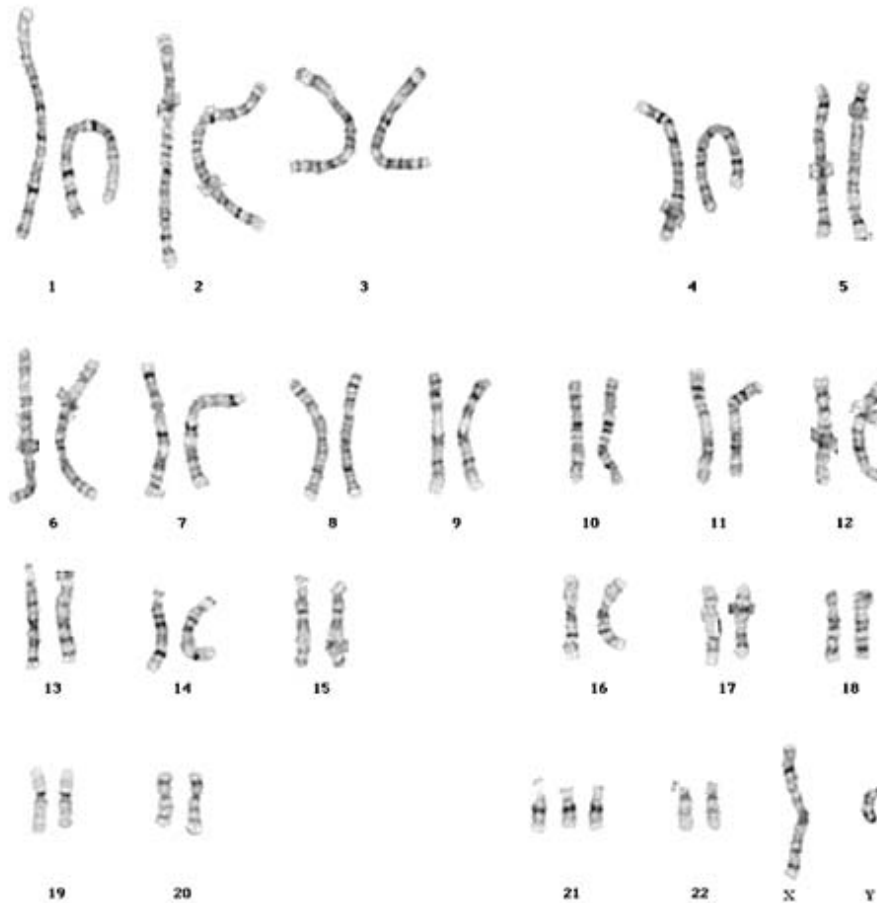
Sometimes, meiosis does not happen perfectly, so the chromosomes are not divided completely equally between the daughter cells produced by meiosis. For example, an egg or a sperm may receive two copies of the same chromosome.

If a human egg receives an extra copy of a chromosome, and this egg is fertilized by a normal sperm, how many copies of this chromosome would there be in the resulting zygote?

How many copies of this chromosome would there be in each cell in the resulting embryo?

When a cell has three copies of a chromosome, the extra copies of the genes on this chromosome result in abnormal cell function and abnormal embryonic development. Therefore, in most cases, a zygote which has an extra chromosome will die early in embryonic development, resulting in a miscarriage.

However, some babies are born with an extra copy of a small chromosome (chromosome 21), and this results in the condition known as Down Syndrome. A karyotype of a boy with Down Syndrome is shown below.⁴ Multiple abnormalities result from the extra copy of chromosome 21 in each cell, including mental retardation, a broad flat face, a big tongue, short height, and often heart defects.



To understand how an extra copy of one chromosome could result in abnormalities, remember that each chromosome has genes with the instructions to make specific types of proteins, so the extra chromosome could result in too many copies of these particular proteins. Think about what might happen if you added too much milk to a box of macaroni and cheese. The macaroni and cheese would have too much liquid and be runny instead of creamy. Cells are much more complicated than mac and cheese, and a cell cannot function properly when there are too many copies of some types of proteins due to an extra copy of one of the chromosomes. When the cells in an embryo do not function properly, the embryo may develop abnormalities and often dies.

⁴ In this karyotype it is difficult to see the sister chromatids in each chromosome, since they are very close to each other.